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Grazing angle enhanced backscattering from a dielectric film on a reflecting metal substrate

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Abstract. We have recently observed several features from a randomly rough dielectric film on a reflecting metal substrate including a change in the spectrum of light at the satellite peaks, the high-order correlation, and enhanced backscattering from the grazing angle. In this paper, we focus on the enhanced backscattering phenomena. The backscattering signal at small grazing angles is very important for vehicle re-entrance and subsurface radar sensing applications. Recently, we performed an experimental study of far-field scattering at small grazing angles, especially enhanced backscattering at grazing angles. For a randomly weak, rough dielectric film on a reflecting metal substrate, a much larger enhanced backscattering peak is measured. Experimental results are compared with theoretical predictions based on a two-scale surface roughness scattering model.
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1 Introduction

Interference effects with diffuse light have been studied for a long time. A recorded observation of the phenomenon was made by Newton about three centuries ago,[1] with a description of the appearance of a series of colored rings that occurs when a beam of sunlight falls on a concave, dusty back-silvered spherical mirror. The phenomenon was explained later by Young,[2] Herschel,[3] and Stokes[4] by considering the interference between two streams of light: one scattered on entering the glass and the other scattered on emerging from the glass. The attention to this phenomena was attracted once and again many times during the last two centuries (see, for example, Raman and Datta,[5] and the bibliography in de Witte[6] and Francon[7,8]). During the last several decades this problem again has received attention owing to numerous applications in modern optics and microelectronics[9–16] and radio-physical methods of solving remote sensing problems for natural layered media.[17–25]

For scattering of light from a rough dielectric film on a reflecting substrate, there are three main kinds of trajectories that give rise to (a) Quetelet fringes, (b) Selenyi fringes, and (c) enhanced backscattering. A typical Quetelet ring pattern consists of a series of elongated, colored diffuse rings. The white ring, corresponding to the zero order of interference, passes through both specular and backscattering directions, and as the angle of incidence is changed, new colors emerge from the center.

Besides the Quetelet-type ring, there is another kind of interference effect that has been observed in the scattering of light from dusty, back-silvered mirrors. The Selenyi rings[26] present a different kind of behavior under oblique illumination; there is no zero-order ring, and the rings are always centered around the normal to the sample. The occurrence of such rings has been explained in terms of the interference between waves scattered back directly from the top of the scattering layer without entering it, and waves reflected by the mirror after first having been scattered when entering the film.

One of the most interesting phenomena associated with the scattering of light from a randomly rough surface is that of enhanced backscattering. This is the presence of a well-defined peak in the retroreflection direction in the angular distribution of the intensity of the incoherent component of the light scattered from such a surface. It results primarily from the coherent interference of each multiply reflected optical ray with its time-reversed partner. For rougher metallic surfaces, where the rms roughness is about 1 to 3 μm, the enhanced backscattering was measured with high-sloped single-scale Gaussian random rough surfaces.[27] For weakly rough metallic surfaces, where the rms roughness is about 0.01 μm, the enhanced backscattering was predicted in a perturbation calculation and subsequently measured.[28,29]

The scattering of light from a one-dimensional randomly rough dielectric film deposited on a flat reflecting substrate has been studied.[30,31] In particular, here we investigate the appearance of well-defined fringes in the angular distribution of the diffusely scattered intensity and their dependence on the angle of incidence, the roughness of the film, and the film's mean thickness. It was found that, for slightly rough films, the angle of incidence modulates the intensity of the fringes but has no effect on their angular position. For rougher films there is less contrast in the pattern, and the fringes move with the angle of incidence in such a way

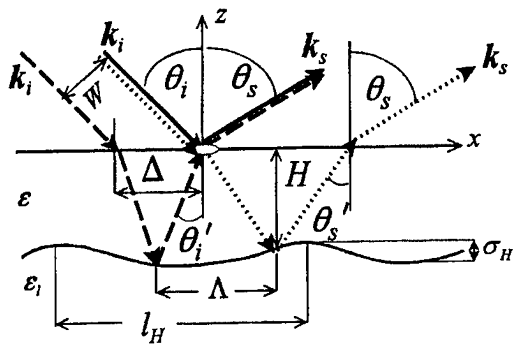


Fig. 1 Physical schematic with indicatrix scattering.

that there are always bright fringes in the specular and backscattering directions. Eventually, for very rough films, the fringe pattern disappears, and a well-defined backscattering peak emerges in a retroreflection direction.

The measurement of the scattering of electromagnetic waves from a randomly rough surface at grazing angles of incidence presents a challenging problem;[32] this is due at least in part to the fact that if, for example, a one-dimensional random surface is illuminated by a beam of finite width W (see Fig. 1), its intercept with the mean scattering surface $\Delta = W/\cos(\theta_i)$, where θ_i is the angle of incidence measured counterclockwise from the normal to the mean scattering plane, increases to a very large value as θ_i approaches 90 deg. For example, if $\theta_i = 89$ deg, $\Delta = 57.3W$. We have to select a small beam size W—about 1.5 mm. Sample length L of the random surface should be large enough to compromise the grazing angle edge effect; L is therefore chosen to be 200 mm.

The theoretical interpretation of observed interference effects usually is based on two main approaches. For large roughness, where rms height exceeds essentially the light wavelength, the tangent plane method, based on Kirchhoff diffraction integral, is employed. For the problem of scalar waves scattering by a rough surface it was applied first by Brekhovskikh[33] and generalized by Isakovich[34] for electromagnetic wave scattering by random rough surfaces. The detailed statement of this method and its further development can be found, e.g., in the monographs of Beckmann and Spizzichino,[35] Bass and Fuks,[36] Ishimaru,[37] and Voronovich.[38]

In the opposite limiting case of smooth interfaces with small roughness, where rms height is much smaller than the light wavelength, the small perturbation method is employed. In the papers of Elson,[39–42] Elson et al.,[43–45] Bousquet et al.,[46] and Duparre et al.[47] it was developed for electromagnetic wave scattering ("vector scattering model") by rough interfaces of multilayer dielectric stacks. This model was successfully applied and developed by Amra[48–50] and Amra et al.[51–54] for a theoretical interpretation of numerous experimental results.

In this paper, we report the observation of enhanced backscattering at grazing angles for a very smooth dielectric film on a reflecting metal substrate. For theoretical interpretation of obtained experimental results, we apply the combination of two mentioned above methods: the small perturbation theory for surface microroughness, and the tangent plane method for large-scale roughness, which can be considered as layer thickness variations as well. This approach is similar to the "two-scale scattering model" commonly used for interpretation of radio wave and sound scattering by natural rough surfaces (see, e.g., Bass and Fuks[36]). The main difference is that in radio-physics and acoustics applications, the large-scale roughness effects in the scattering process by the angular modulation of the microroughness scattering indicatrix are obtained in the framework of the small perturbation method. Here, the large-scale roughness is assumed to be very gentle with negligible slopes, and they effect scattering only by phase disturbances of multiple reflecting waves propagating inside the layered structure. Section 2 will introduce this theoretical analysis, followed by Section 3, the experimental results, and Section 4, the summary.

2 Theoretical Analysis

2.1 *Small Perturbation Theory*

Here, we consider the small perturbation theory application to the specific case of a plane-stratified dielectric medium with only one rough surface separating it from the free space (in particular, it can be the "upper interface" of the multilayer dielectric stack). For this scattering problem, there is no need to use the general form of vector scattering theory developed in Refs. 39–47 for multilayer dielectric stacks with an arbitrary number of rough interfaces. We can employ for this specific case the simplified and more compact version of this theory reported in Fuks and Voronovich[55] and Fuks.[56]

It is assumed that the surface roughness height $\varsigma(\mathbf{r})$ (where $\mathbf{r} = \{x,y\}$ is a radius-vector in the plane $z=0$ of the medium boundary) is much smaller than the incident wavelength λ. The specific (related to the unit area of surface $z=0$) scattering cross-section $\sigma^0_{\alpha\beta}(\mathbf{k}_s, \mathbf{k}_i)$ of the plane incident wave with wave vector $\mathbf{k}_i$ (see Fig. 1) and polarization state $\beta = p,s$ [s polarization corresponds to the direction of electric vector, which is perpendicular to the plane of incidence xOz, and p polarization corresponds to the electric vector that lies in this plane] into the scattered plane wave with wave vector $\mathbf{k}_s = (k_0 \sin\theta_s \cos\varphi_s, k_0 \sin\theta_s \sin\varphi_s, k_0 \cos\theta_s)$ and polarization state $\alpha = p,s$ [s polarization corresponds to the electrical vector that is perpendicular to the plane of scattering, which forms the azimuthal angle φ with the plane of incidence xOz, and p polarization corresponds to the electrical vector that lies in this plane] can be written in the following form [see Eq. (5.3) in Fuks[56]]:

$$\sigma^0_{\alpha\beta}(k_s, k_i) = \pi k_0^4 |\varepsilon - 1|^2 |f_{\alpha\beta}|^2 S_\varsigma(q_\perp), \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wave number, $\varepsilon \equiv \varepsilon(0)$ is the upper-limit value of the dielectric permittivity $\varepsilon(z)$ in the medium ($z<0$), $\mathbf{q} = \mathbf{k}_s - \mathbf{k}_i$ is a vector of scattering, $\mathbf{q}_\perp$ is its projection on the plane $z=0$, and $S_\varsigma(\mathbf{q}_\perp)$ is a spatial power spectrum of surface roughness, which can be introduced as a Fourier transformation of roughness autocorrelation function $W(\rho) = \varsigma(r+\rho)\varsigma(\rho)$:

$$S_\varsigma(\mathbf{p})=\frac{1}{(2\pi)^2}\int\int W(\rho)e^{ip\rho}d\rho, \tag{2}$$

where the bar $\overline{...}$ denotes the statistical averaging over the ensemble of random function $\varsigma(\mathbf{r})$, and factors $f_{\alpha\beta}$ (which are proportional to the amplitude, or length of scattering) are given by the expressions (5.6) to (5.9) from Fuks[56]:

$$f_{ss}=[1+R_s(\theta_i)][1+R_s(\theta_s)]\cos\varphi, \tag{3}$$

$$f_{ps}=-\lfloor 1-R_p(\theta_s)\rfloor[1+R_s(\theta_i)]\cos\theta_s\sin\varphi, \tag{4}$$

$$f_{pp}=\frac{1}{\varepsilon}[1+R_p(\theta_i)][1+R_p(\theta_s)]\sin\theta_i\sin\theta_s-[1-R_p(\theta_i)]\times[1-R_p(\theta_s)]\cos\theta_i\cos\theta_s\cos\varphi \tag{5}$$

$$f_{sp}=\lfloor 1-R_p(\theta_i)\rfloor[1+R_s(\theta_s)]\cos\theta_i\sin\varphi. \tag{6}$$

Here, R_s and R_p are the specular reflection coefficients from the lower ($z<0$) stratified media into the upper half-space ($z>0$) for s and p polarizations, correspondingly.

In the particular case of uniform (homogeneous) media with $\varepsilon(z)=\varepsilon=\text{const}$, when there is no volume scattering at all in the half-space $z<0$, coefficients R_p and R_s coincide with the usual Fresnel reflection coefficients R_{0p} and R_{0s} from the plane interface of two homogeneous media ($\varepsilon_0=1$, $z>0$) and (ε, $z>0$):

$$R_{op}=\frac{\varepsilon\cos\theta-\sqrt{\varepsilon-\sin^2\theta}}{\varepsilon\cos\theta+\sqrt{\varepsilon-\sin^2\theta}};\quad R_{os}=\frac{\cos\theta-\sqrt{\varepsilon-\sin^2\theta}}{\cos\theta+\sqrt{\varepsilon-\sin^2\theta}}. \tag{7}$$

In the general case of an arbitrary stratified medium, the reflection coefficients R_p and R_s can be represented in the form

$$R_{p,s}=\frac{R_{0p,s}+R'_{p,s}}{1+R_{0p,s}R'_{p,s}}, \tag{8}$$

where $R'_{p,s}$ are the reflection coefficients from the buried layers ($R'_{p,s}=0$ for the uniform $\varepsilon(z)=\text{const}$ homogeneous half-space $z<0$).

2.2 *Scattering in Presence of Large-scale Roughness*

Here, we apply the above equations to the simplest case of layered structure: the homogeneous dielectric layer of thickness H and permittivity ε lying on the homogeneous half-space ($z\leqslant H$) with a complex dielectric permittivity constant ε_1. The reflection coefficient $R_{p,s}(\theta)$ from this structure for every linear polarization (s,p) is given by Eq. (8), where $R'_{p,s}(\theta)$ can be written in the form $R'_{p,s}(\theta)=R_{1p,s}(\theta)\exp[i\varphi(\theta)]$, where $R_{1p,s}(\theta)$ is the Fresnel reflection coefficient from the interface of two media with dielectric permittivity constants ε and ε_1:

$$R_{1s}=\frac{\sqrt{\varepsilon-\sin^2\theta}-\sqrt{\varepsilon_1-\sin^2\theta}}{\sqrt{\varepsilon-\sin^2\theta}+\sqrt{\varepsilon_1-\sin^2\theta}};$$

$$R_{1p}=\frac{\varepsilon_1\sqrt{\varepsilon-\sin^2\theta}-\varepsilon\sqrt{\varepsilon_1-\sin^2\theta}}{\varepsilon_1\sqrt{\varepsilon-\sin^2\theta}+\varepsilon\sqrt{\varepsilon_1-\sin^2\theta}} \tag{9}$$

and $\varphi(\theta)=2k_0H\sqrt{\varepsilon-\sin^2\theta}$.

A detailed analysis of the intensity spatial distribution pattern, originated from scattered-by-roughness $z=\varsigma(\mathbf{r})$ and multiply-reflected (from planes $z=0$ and $z=-H$) wave interference, was done by Fuks[56]: the interference rings, angular positions, their polarization dependence, periods of intensity oscillations as functions of parameters H and λ, etc. These theoretical results are in good agreement with experiments carried out with the perfect Fabry-Pérot parallel-slided plates ($H=\text{const}$) and the very small surface settled scatterers (see, e.g., de Witte[6]). But in some experiments (see Kaganovskii et al.[57]) an essential disagreement with this theory was discovered. It was shown that large-scale roughness (LSR) can be the main reason of destruction of the interference between some types of waves, which leads to the "survival" of only one specific set of interference maxima and the suppression of others. The theoretical analysis conducted in Kaganovskii et al.[57] was restricted to consideration of interference of once-reflected waves only. For a very low grazing angle of incidence $\pi/2-\theta_i$ the multiple wave reflections into the resonator formed by two planes $z=0$ and $z=-H$ can play the leading role in forming the scattered field intensity spatial distribution, and in particular, in forming the backscattering intensity peak.

To investigate the effect of LSR on the scattered intensity distribution, we assume that the successive wave reflections inside the layer ($0>z>-H$) take place every time from a horizontal plane, as depicted in Fig. 1, without changing the reflective angles θ'_i and θ'_s, correspondingly, before and after scattering by the rough patch of the upper boundary. The layer thickness H is different at the different points of reflection, as shown also in Fig. 1. The solution of this modeling problem can be represented in the form of Eq. (1) with amplitudes $f_{\alpha\beta}$, which can be obtained from those given by Eqs. (3)–(6), with the following formal procedure. In $f_{\alpha\beta}$, represented by the above-mentioned equations, the factors $\lfloor 1\pm R_{s,p}\rfloor$ can be rewritten in the following form, using Eq. (8):

$$1\pm R=\frac{R_0\pm 1}{R_0}\left[1\pm\frac{R_0\mp 1}{1+R_0R'}\right]. \tag{10}$$

Here, for brevity, we omit the arguments (θ_i and θ_s) or only their subscripts (i and s), and the polarization subscripts (p and s) in reflection coefficients, to avoid confusion. We expand Eq. (10) in a series of $R'=R_1\exp[i\varphi]$ powers, which is equivalent to field representation as a series of multiple reflections. We substitute instead $n\varphi$, the phase of the wave n-times reflected from the undulated interface between layer and substrate $n\varphi\Rightarrow\Sigma_{k=1}^{n}\phi_k$, where

$\varphi_k(\theta)=2k_0H_k\sqrt{\varepsilon-\sin^2\theta}$, and $\{H_k\}$ is the set of layer thicknesses in the specularly reflecting points:

$$1\pm R\Rightarrow\frac{R_0\pm1}{R_0}\left[1\pm(R_0\mp1)\sum_{n=0}^{\infty}(-R_0R_1)^n\times\exp\left(i\sum_{k=1}^{n}\phi_k\right)\right]. \tag{11}$$

Now we can consider H as a random function of two variables (x,y), with a given average value $\langle H\rangle$, variance σ_H^2, and correlation length l_H.

Here, we assume that there are no losses inside the dielectric layer, i.e., $\mathrm{Im}\,\varepsilon=0$, and present results only for the limiting case of extremely strong variations of layer thickness σ_H^2, when the corresponding Rayleigh parameter essentially exceeds unity, i.e.,

$$\langle(\delta\phi_k)^2\rangle=4k_0^2\sigma_H^2(\varepsilon-\sin^2\theta_s)=(2k_1\sigma_H\cos\theta_s')^2\gg1, \tag{12}$$

where θ_s' and θ_s are related by Snell's refraction law: $\sin\theta_s'=\sin\theta_s/n$, $n=\sqrt{\varepsilon}$ is a refraction index, and $k_1=nk_0$. If this inequality holds, it is possible to neglect the averaged value of exponents in Eq. (11); i.e., take $\langle\exp(i\phi_k)\rangle=0$ in all equations that appear from Eq. (11).

The result of statistical averaging of scattered light intensity angular distribution over the set of random variables $\{H_k\}$, which we denote by the corner brackets $\langle\ldots\rangle$, strongly depends on the ratio of correlation length l_H and the distances Λ between the sequential specular reflecting points (see Fig. 1). If all distances Λ between every two arbitrary reflecting points from the substrate exceed essentially the correlation length l_H, then all subsequent specular reflections from the lower layer boundary can be considered as independent random events, and consequently, the set of ϕ_k is the set of independent variables. Thus, if inequality $\Lambda\gg l_H$ holds, then in all directions of scattering given by angles θ_s,φ, excluding the vicinity of backscattering direction ($\theta_s=\theta_i$, $\varphi=\pi$), the factors $1\pm R(\theta_i)$ and $1\pm R(\theta_s)$ are statistically independent and can be averaged separately. The statistical average value of the scattering cross-section $\langle\sigma_{\alpha\beta}^0\rangle$ over layer thickness fluctuations $\delta H=H-\langle H\rangle$ is proportional to the $\langle|f_{\alpha\beta}|^2\rangle$, which for s polarization takes the form [see Eq. (3)]:

$$\langle|f_{ss}|^2\rangle=\langle|1+R_s(\theta_i)|^2\rangle\langle|1+R_s(\theta_s)|^2\rangle\cos^2\varphi. \tag{13}$$

Compare the scattering cross-section $\langle\sigma_{ss}^0\rangle$, averaged over the layer thickness variations, with the corresponding value $\bar{\sigma}_{ss}$ for the homogeneous half-space bounded by the same rough surface. The explicit equation for $\bar{\sigma}_{ss}$ is given by Eq. (1) with f_{ss} from Eq. (3), where the reflection coefficients R_s have to be substituted by R_{0s}; i.e., if we insert $R_s'=0$ into all the above equations. For the ratio of these two cross-sections (which can be named, according to Kalmykov et al.,[58] as a contrast coefficient K_{ss}), we obtain:

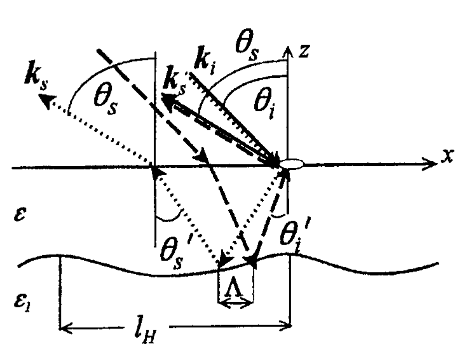


Fig. 2 Physical schematic for a near backscattering direction.

$$K_{ss}=\frac{\langle\sigma_{ss}^0\rangle}{\bar{\sigma}_{ss}}=C(\theta_i)C(\theta_s), \tag{14}$$

where function $C(\theta)$ is given by the equation

$$C(\theta)=\frac{1+r_1^2(1+2r_0)}{1-(r_0r_1)^2}, \tag{15}$$

where $r_0=|R_{0s}|$ and $r_1=|R_{1s}|$. In the special case of a perfectly conducting substrate, when $r_1=1$, Eq. (15) takes the form

$$C(\theta)=\frac{2}{1-r_0(\theta)}, \tag{16}$$

and we obtain the simple equation for the contrast coefficient, introduced by Eq. (14):

$$K_{ss}(\theta_s,\theta_i)=\frac{4}{[1-r_0(\theta_i)][1-r_0(\theta_s)]}. \tag{17}$$

It follows from this equation that $K_{ss}(\theta_s,\theta_i)\geq4$, because $0\leq r_0(\theta_{i,s})\leq1$, and in the particular case of $\varepsilon\gg1$, when

$$1-r_0(\theta)=\frac{2\cos\theta}{\sqrt{\varepsilon-\sin^2\theta}+\cos\theta}\cong\frac{2\cos\theta}{\varepsilon}, \tag{18}$$

we obtain for $K_{ss}(\theta_s,\theta_i)$:

$$K_{ss}(\theta_s,\theta_i)=\frac{\varepsilon}{\cos\theta_s\cos\theta_i}\gg1. \tag{19}$$

It is seen that the average brightness of the interference pattern due to the substrate can essentially exceed the one for a homogeneous half-space (without substrate) even for very strong variations of layer thickness δH when all the interference maxima are completely smoothed.

2.3 *Backscattering Enhancement*

The backscattering case has to be considered separately because the dashed and dotted ray trajectories in Fig. 2 are fully congruent in this case, and it is impossible to carry out the averaging over δH separately for each of them. When

$\theta_s = \theta_i$ and $\varphi = \pi$, and all specular reflecting points for dashed and dotted rays coincide, we have to carry out the following averaging:

$$\langle \sigma_{ss}^0 \rangle \approx \langle |1 + R_s(\theta_i)|^4 \rangle, \tag{20}$$

where $1 + R_s(\theta_i)$ is represented as the sum Eq. (11) of independent specular reflections from the undulated substrate.

Omitting the bulky derivations, we present here only the final expression for the contrast coefficient K_{0ss} in a backscattering direction as a result of averaging in the limiting case of very strong layer thickness fluctuations δH, when the inequality Eq. (12) holds:

$$K_{0ss} = \frac{\langle |1+R_s|^4 \rangle}{|1+R_{0s}|^4} = \{(1+r_1^2)[(1+r_1^2)(1+A)+8r_1^2 r_0] + 2r_1^2[(1-A)^2+2A(3-A)]\}(1-A)^{-3}, \tag{21}$$

where $A = (r_0 r_1)^2$ and θ_i is supposed to be an argument for all reflection coefficients. Compare K_{0ss} given by Eq. (21) with the indicatrix contrast coefficient K_{ss} given by Eq. (14) for directions of scattering θ_s close to backscattering; i.e., inserting $\theta_s = \theta_i$ and $\mathbf{k}_s = -\mathbf{k}_i$, we can estimate the excess γ of the backscattering peak of $\langle \sigma_{ss}^0(-\mathbf{k}_i, -\mathbf{k}_i \rangle$ over the surrounding background:

$$\gamma = \frac{K_{0ss}}{K_{ss}}. \tag{22}$$

Equation (21) takes the simpler form for the specific case of a perfectly conducting substrate when $r_1 = 1$:

$$K_{0ss} = \frac{2(3-r_0)}{(1-r_0)^3}. \tag{23}$$

Compare this expression with the indicatrix contrast coefficient K_{ss} given by Eq. (17) for directions of scattering θ_s close to backscattering; i.e., inserting $\theta_s = \theta_i$:

$$K_{ss} = \frac{4}{[1-r_0(\theta_i)]^2}. \tag{24}$$

We can estimate the excess γ of a backscattering peak of $\langle \sigma_{ss}^0(-\mathbf{k}_i, -\mathbf{k}_i \rangle$ over the surrounding background, in this specific case:

$$\gamma = \frac{(3-r_0)}{2(1-r_0)}. \tag{25}$$

It is easy to see that the general phenomenon of backscattering enhancement, in the specific problem under consideration, appears as a backscattering peak enhancement, which for $(1-r_0) \ll 1$ can essentially (many times) exceed the background, in contrast to the well-known volume scattering problem, where this enhancement can achieve only the value of several units. In the specific case of low grazing angle or large layer dielectric permittivity ε, when inequality $\sqrt{\varepsilon - \sin^2\theta_i} \gg \cos\theta_i$ holds, from Eq. (25) it follows that:

$$\gamma = \frac{\sqrt{\varepsilon - \sin^2\theta_i}}{2\cos\theta_i} \gg 1. \tag{26}$$

It is worth emphasizing that none of the above equations for contrast coefficients K_{ss} and K_{0ss}, as well as for backscattering peak enhancement γ, depends on the statistical parameters of upper surface roughness, and in particular, on its spatial power spectrum $S_\varsigma(\mathbf{q}_\perp)$. For a nonabsorptive dielectric layer with $\mathrm{Im}\,\varepsilon = 0$ neither do they depend on the mean layer thickness $\langle H \rangle$ and its variance σ_H^2, if the inequality Eq. (12) holds.

3 Experimental Results

The fully automated bidirectional reflectometer shown in Fig. 3 is used to measure the fraction of incident light reflected by the sample into incremental angles over its field of view. It uses illumination from laser sources at 0.633 μm and enables measurements to be taken for any combination of incident and reflected angles over the entire plane, except for a small angle (about 0.5 deg away from the retroreflection direction) in which the source and detector mirrors interfere. A laser beam passes through a polarizer and is interrupted by a chopper and a half-wavelength plate, which enables rotation of the polarization of the beam. Then it is directed toward the sample by a folded beam system that collimates it into a parallel beam up to 25 mm in diameter. For our measurement, the beam size is set to 1.5 mm. The sample is viewed by a movable off-axis paraboloid that projects the light reflected by the sample onto the detector via a polarizer and a folding mirror. Four different polarization combinations of input and receiving beams are recorded. The reference standard used for these experiments is Lab Sphere Gold, and the relative bidirectional reflectance is measured. The signal is recorded and digitized at each angular setting of interest throughout the angular range by an ITHACO lock-in amplifier and the data are stored in the memory of a personal computer (PC). The sample and the receiving telescope arm are separately mounted on two rotational stages run by two independent stepper motors that are controlled by the PC via a two-axis driver.

The sample we used is made of smooth aluminum that was coated with a dielectric film for high performance and protection. The thickness of the layer is approximately $H = 5.2\,\mu$m. The complex permittivity ε_1 of Al at $\lambda = 0.6328\,\mu$m is $\varepsilon_1 = -56.52 + 21.25i$. The refractive index of the film is $n = 1.64$ (the dielectric constant is $\varepsilon = 2.69$). The sample was characterized with a Dektak 3030 stylus machine. The stylus radius was approximately 0.15 μm, and a total of 2000 points over a 2-mm profile were taken for each trace. From a statistical analysis of 10 profiles it was determined that the rms height of the roughness of the film was about 0.06 μm and the approximate value of $1/e$ correlation length of the roughness was about 0.3 μm. The illuminating source in the experiment is a 15-mW He-Ne laser with $\lambda = 0.6328\,\mu$m. Since the dielectric film is

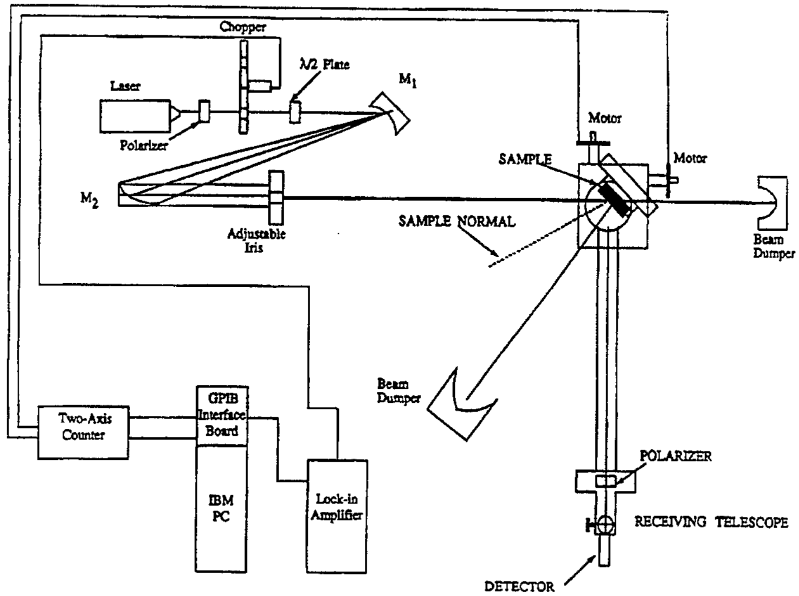


Fig. 3 Schematic of the bidirectional reflectometer.

smooth, most of the energy goes in a specular direction, thus a sensitive photomultiplier is used.

In the experiment, the beam size is set to $W=1.5$ mm. Since the beam size is small, the average far-field speckle size is large. We have to average about 100 measurements to obtain the far-field scattering at each angle by scanning very small yaw and pitch directions of the sample.

Figure 4(a) shows the experimental results for p polarization, and Fig. 4(b) for s polarization with $\theta_i = -89$ deg. There is a large enhanced backscattering peak at near grazing angle $\theta_s = 89$ deg. The ratio of the backscattering enhancement peak over the surrounding background at $\theta_s = 89$ deg for p polarization is about 19.6, and the ratio of the backscattering enhancement peak over the surrounding background at $\theta_s = 89$ deg for s polarization is about 20.4. However, in the experiment, the backscattering peak has a finite width, and considerable uncertainty appears in determining the peak excess over the surrounding background.

The dependence of K_{0ss} on the angle of incidence θ_i is calculated for layer parameters, corresponding to the experiment described above, and shown in Fig. 5. It is seen that for the very low grazing angle, the backscattering contrast K_{0ss} can achieve values of several thousands. The plot of $\gamma(\theta_i)$ presented in Fig. 6 shows the layer parameters corresponding to the experimental curve in Fig. 4(b). For $\theta_i = 89$ deg, the backscattering peak excess $\gamma \cong 20$ approximately coincides with the value observed in the experiment.

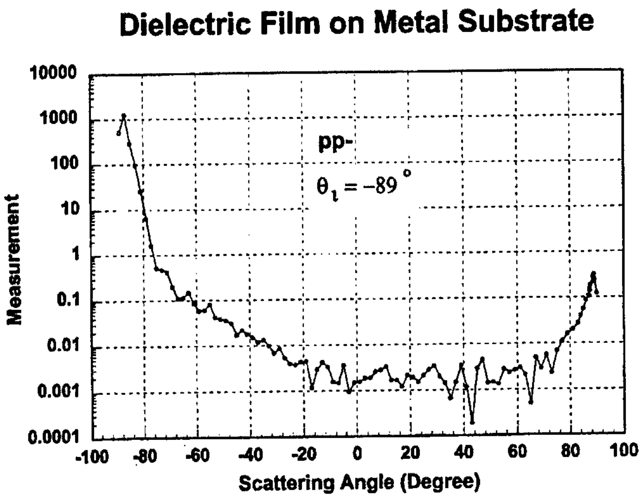
4 Summary

We have observed several features from a randomly rough dielectric film on a reflecting metal substrate including a change in the spectrum of light at the satellite peaks, the high-order correlation, and enhanced backscattering from the grazing angle. In this paper we have focused on the enhanced backscattering phenomena at the grazing angle.

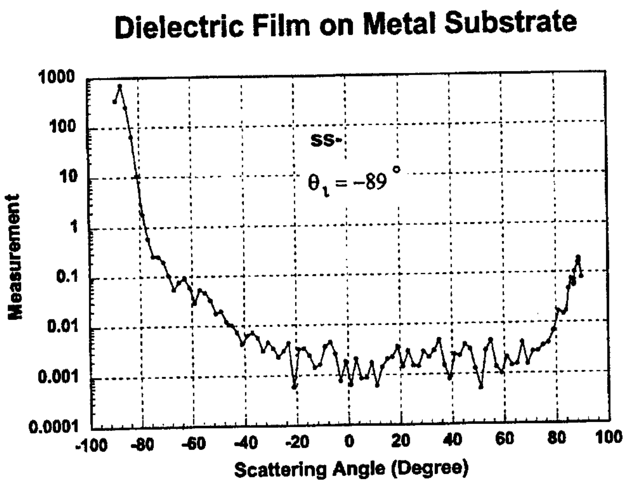
Recently, the coherence theory predicted that the correlation in the fluctuations of a source distribution can cause frequency changes in the spectrum of the emitted radiation, even when the source is at rest relative to the observer.[59] Because of the close analogy that exists between the processes of radiation and scattering, a similar effect is expected to occur when radiation is scattered by a static medium or rough target. This phenomenon also has a significant relationship to enhanced backscattering, which is one of the most interesting phenomena associated with the scattering of light from a randomly rough surface. This is described as the presence of a well-defined peak in the retroreflection direction in the angular distribution of the intensity of the incoherent component of the incident beam scattered from such a surface. For metallic optical rough surfaces, the high-slope nature of the surface leads to multiple scattering and this contribution enhances the scattered light.[27] For a weak corrugated metallic surface, it is due to the multiple scattering of the surface polaritons excited by the incident light passing through the hills and valleys on the surface before they are converted back into volume waves in the vacuum, propagating away from the surface.[28,29] The coherent interference of such a scattering sequence and its time-reversed partner leads the enhanced backscattering in the retro-reflection direction.

In our case, the multipath propagation is caused not by multiple scattering by surface roughness, but the multiple specular reflections of waves between two surfaces: the metallic substrate and the upper boundary of the dielectric film. To obtain the effect of backscattering enhancement, it is enough to consider only single scattering by a dielectric film micro-roughness and perform statistical averaging over the large-scale roughness, with negligible slopes, which is equivalent to the film thickness smooth variations.

The scattering of electromagnetic waves from randomly rough surfaces near the grazing incident angle is of widespread interest in various physical situations, in particular



(a)



(b)

Fig. 4 Experimental results for (a) p polarization and (b) s polarization.

coastal and shipborne radar backscatter. It is, however, a very difficult problem, with issues such as sea spikes and unexpectedly large parallel-parallel scattering cross-sections, still awaiting a satisfactory analytical solution.

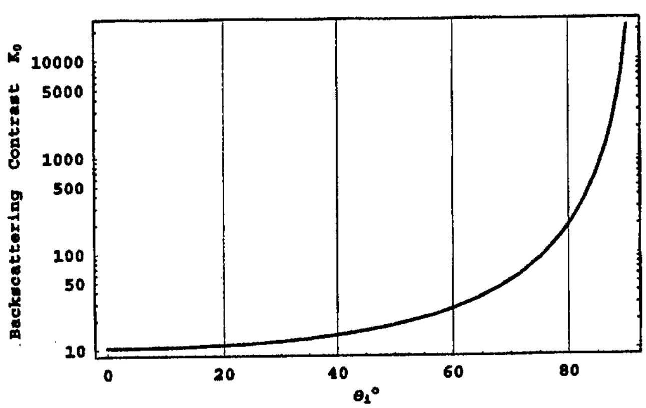


Fig. 5 Backscattering contrast coefficient K_{oss}.

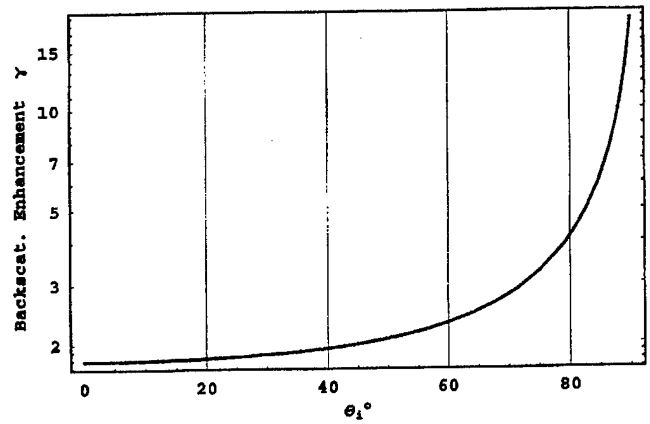


Fig. 6 Backscattering peak enhancement γ.

Backscattering signals at small grazing angles are very important for vehicle re-entrance and lidar signature applications. For a randomly weak, rough dielectric film on a reflecting metal substrate, a much larger enhanced backscattering at $\theta_s = 89$ deg is measured, which is compared with a theoretical calculation. Due to Quetelet's rings, the energy of diffusion is redistributed and a large portion of energy is attracted to the retro-reflection direction at the grazing angle. For this reason, a large backscattering peak appears on the grazing angle.

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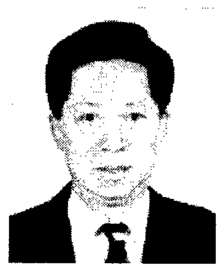

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Mikael Ciftin: Biography and photograph not available.